Chapter 1 An Analysis of MIMO Techniques for Mobile WiMAX Systems

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Multiple input multiple output (MIMO) techniques are an essential part of of the IEEE 802.16e - 2005 specifications, which form the basis of mobile WiMAX systems. In this chapter, we first discuss the basic tradeoffs between diversity, interference cancellation and spatial multiplexing in MIMO systems, and we compare optimum combining (OC), maximum-ratio combining (MRC) and interference cancellation for different numbers of receive antennas. Then, we focus on the two mandatory MIMO profiles in the IEEE specifications (Alamouti's STC and the 2x2 spatial multiplexing scheme) and compare them when the first is combined with MRC at the receiver. The simulations made using the ITU pedestrian B channel indicates that Alamouti's STC outperforms spatial multiplexing when the two schemes are operated at the same spectral efficiency. We next give signal-to-noise ratio (SNR) thresholds for the operating regions of different modulation, coding and MIMO schemes included in WiMAX system specifications.

1.1 Introduction

Mobile WiMAX systems are based on the IEEE 802.16e-2005 specifications [1] which define a physical (PHY) layer and a medium access control (MAC) layer for mobile and portable broadband wireless access systems operating at microwave frequencies below 6 GHz. The IEEE 802.16e-2005 specifications actually define three different PHY layers: Single-carrier transmission, orthogonal frequency-division multiplexing (OFDM), and orthogonal frequency-division multiple access (OFDMA). The multiple access technique used in the first two of these PHY specifications is pure TDMA, but the third mode uses both the time and frequency dimensions for resource allocation. From these 3 PHY technologies, OFDMA [2] has been selected by the WiMAX Forum as the basic technology for portable and mobile services. Compared to TDMA-based systems, it is known that OFDMA leads to a significant cell range extension on the uplink (from mobile stations to base station). This is due to the fact that the transmit power of the mobile station is concentrated in a small portion of the channel bandwidth and the signal-to-noise ratio (SNR) at the receiver input is increased. Cell range extension is also achievable on the downlink (from base station to mobile stations) by allocating more power to carrier groups assigned to distant users. Another interesting feature of OFDMA is that it eases the deployment of networks with a frequency reuse factor of 1, thus eliminating the need for frequency planning.

Since radio resources are scarce and data rate requirements keep increasing, spectral efficiency is a stringent requirement in present and future wireless communications systems.

On the other hand, random fluctuations in the wireless channel preclude the continuous use of highly bandwidth-efficient modulation, and therefore adaptive modulation and coding (AMC) has become a standard approach in recently developed wireless standards, including WiMAX. The idea behind AMC is to dynamically adapt the modulation and coding scheme to the channel conditions to achieve the highest spectral efficiency at all times [3, Chapter 9].

An additional dimension to modulation and coding aimed at increasing spectral efficiency (data rate normalized by the channel bandwidth) is the space dimension, i.e., the use of multiple antennas at the transmitter and receiver. More generally, multiple-antenna techniques can be used to increase diversity and improve the bit error rate (BER) performance of wireless systems, increase the cell range, increase the transmitted data rate through spatial multiplexing, and/or reduce interference from other users. The WiMAX Forum has selected two different multiple antenna profiles for use on the downlink. One of them is based on the space–time code (STC) proposed by Alamouti for transmit diversity [4], and the other is a simple 2x2 spatial multiplexing scheme. These profiles can also be used on the uplink, but their implementation is only optional.

This paper discusses the use of multiple-antenna techniques in mobile WiMAX systems. We first present antenna array techniques, which primarily reduce interference and enhance the useful signal power. Next, we give a general description of multi-input multi-output (MIMO) systems, which can be used for different purposes including diversity, spatial multiplexing and interference reduction. Then, we focus on the multi-antenna profiles adopted for WiMAX systems, discuss their relative merits, and address the implementation issues.

1.2 Multiple Antenna Systems

The performance improvement that results from the use of diversity in wireless communications is well known and often exploited. On channels affected by Rayleigh fading, the BER is known to decrease proportionally to SNR^{-d}, where SNR designates the signal-to-noise ratio and d designates the system *diversity* obtained by transmitting the same symbol through d independently faded channels. Diversity is traditionally achieved by repeating the transmitted symbols in time, in frequency or using multiple antennas at the receiver. In the latter case, the *diversity gain* is compounded to the *array gain,* consisting of an increase in average receive SNR due to the coherent combination of received signals, which results in a reduction of the average noise power even in the absence of fading.

If, in addition to multiple receive antennas, one includes multiple *transmit* antennas, a MIMO system is obtained (see Fig. 1 for a general block diagram).

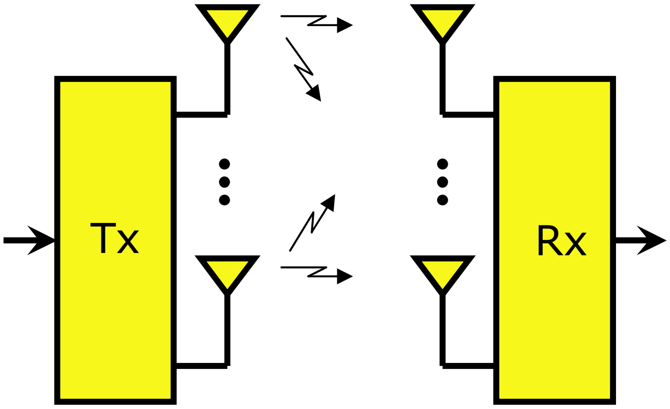

Figure 1 General block diagram of MIMO systems

Here, the situation is more complex, with a greater deal of flexibility in the design and potential advantages at the price of a larger system complexity. In fact, in addition to array gain and diversity gain, one can achieve *spatial multiplexing gain*, realized by transmitting independent information from the individual antennas, and *interference reduction*. The enormous values of the spatial multiplexing gain potentially achieved by MIMO techniques have had a major impact on the introduction of MIMO technology in wireless systems.

A. Antenna Array Techniques

Multiple antennas at the transmitter and the receiver can provide diversity gain as well as increased data rates through space-time signal processing. Alternatively, sectorization or smart (adaptive) antenna array techniques can be used to provide directional antenna gain at the transmitter or at the receiver. This directionality can increase the cell range, reduce channel delay spread and flat-fading, and suppress interference between users. Indeed, interference typically arrives at the receiver from different directions, and directional antennas can exploit these differences to null or attenuate interference arriving from given directions, thereby increasing system capacity. Exploiting the reflected multipath components of the signal arriving at the receiver requires an analysis of multiplexing/diversity/ directionality tradeoff. Whether it is best to use the multiple antennas to increase data rates through multiplexing, increase robustness to fading through diversity, or reduce channel delay spread and interference through directionality is a complex tradeoff decision that depends on the overall system design as well as on the environment (urban, semi-urban, rural).

The most common directive antennas are switched-beam or phased (directional) antenna arrays, as shown in Fig. 2. In these systems, there are multiple fixed antenna beams formed by the array, and the system switches between these different beams to obtain the best performance, i.e., the strongest signal-to-interference-plus-noise-ratio (SINR) of the desired signal. Switched-beam antenna arrays are designed to provide high gain across a range of signal arrival angles, and can also be used to sectorize the directions that signals arrive from. In particular, sectorization is commonly used at base stations to cut down on interference: If different sectors are assigned different frequencies or time slots, then only those users within the same sector interfere with each other, thereby reducing the average interference by a factor equal to the number of sectors. For example, if a 360^o angular range is divided into three sectors to be covered by three 120^o sectorized antennas, then the interference in each sector is reduced by a factor of 3 relative to an omnidirectional base station antenna. The price paid for this reduced interference is the increased complexity of sectorized antennas, including the need to switch a user's beam as it moves between sectors. The benefits of directionality that can be obtained with multiple antennas must be weighed against the potential diversity or multiplexing benefits of the antennas.

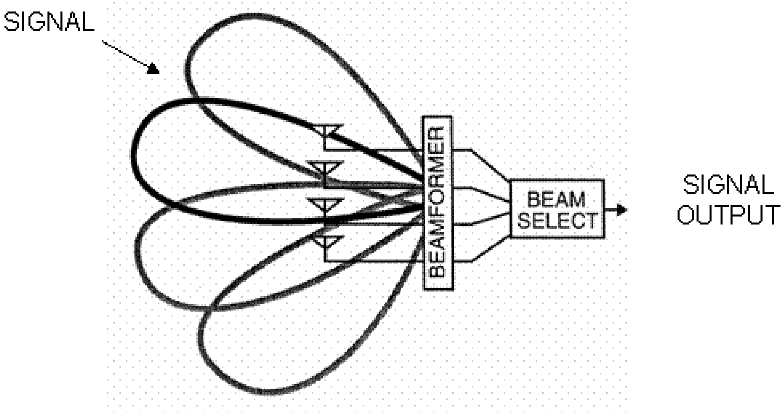

Figure 2 Switched-beam (sectorized) array

Adaptive (smart) antenna arrays typically use phased-array techniques to provide directional gain, which can be tightly controlled with a sufficient number of antenna elements. Phased-array techniques work by adapting the phase of each antenna element in the array, which changes the angular locations of the antenna beams (angles with large gain) and nulls (angles with small gain), as shown in Fig. 3. For an antenna array with N antennas, N nulls can be formed to significantly reduce the received power of N separate interferers. If there are $N_I < N$ interferers, then the N_I interferers can be cancelled out using N_I antennas in a phased array, and the remaining $N\text{-}N_I$ antennas can be used for diversity or multiplexing gain. Note that directional antennas must know the angular location of the desired and interfering signals to provide high or low gains in the appropriate directions, and tracking of user locations can be a significant impediment in highly mobile systems.

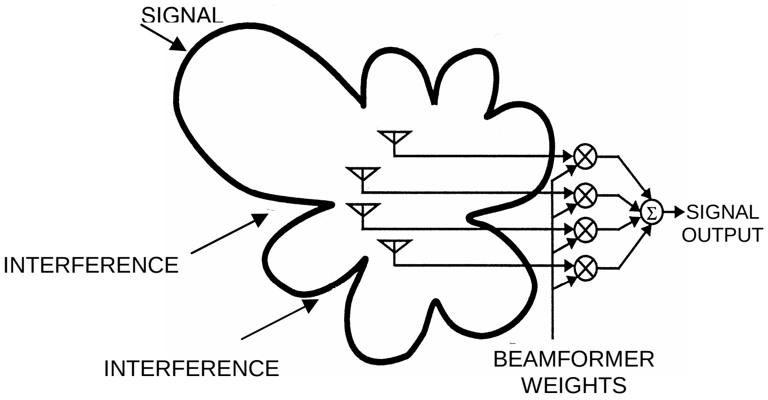

Figure 3 Smart antenna (phased array)

The complexity of antenna array processing, along with the size of a large antenna array, make the use of smart antennas in small, lightweight, low-power handheld devices challenging. However, base stations and access points already use antenna arrays in many cases.

B. Performance Tradeoffs

An adaptive array with *N* antennas can provide the following performance benefits:

a) A higher antenna gain for extended battery life, extended range, and higher throughput

b) Multipath diversity gain for improved reliability, including more robust operation of services

c) Interference suppression

d) Reduced interference into other systems on transmission, and

e) Higher link capacity through the use of MIMO with spatial multiplexing.

More specifically, an antenna array with N_t transmit antennas and N_r receiver antennas provides an array gain (average SNR increase) of $N_t + N_r$ and a diversity gain (BER slope reduction) of N_tN_r. Alternatively, in rich scattering it provides a min(N_t, N_r) multiplexing gain (data rate increase) or it can null out N_r interferers on the receive end. For example, a 4-element antenna array can provide up to a 13 dB SNR gain (7 dB array gain plus a 6 dB diversity gain), or a four-fold increase in data rate assuming four antennas at both the transmitter and receiver, or a cancellation of up to three interfering signals. However, these improvements cannot all be obtained simultaneously (e.g., suppression of N_r–1 interferers and a diversity gain of N_r are mutually exclusive) –yet, each adaptive array in a system can optimize its performance in different combinations of a) through e) depending on its situation.

The performance tradeoffs between diversity and multiplexing for antenna arrays are well known [3, 5], and recent developments in space-time codes achieve the fundamental tradeoff performance bounds. However, the tradeoff between interference cancellation (IC) and diversity gain is not well understood. Recent work [6] has explored this tradeoff to obtain the best use of multiple receive antennas in fading channels with interference. This work obtains closed-form expressions for the performance analysis of different antenna array processing schemes based on the outage probability under maximal ratio combining (MRC), optimum combining (OC) [7], and interference cancellation through beam steering. Though OC is known to be the optimum technique in the presence of interference, providing diversity and interference cancellation simultaneously, its implementation complexity is high. Therefore, it may be best to use combined MRC (to provide diversity) and IC (to suppress the strongest interferers). The results in [6] show that IC yields significantly better performance than MRC if the system is interference limited and the number of dominant interferers is lower than the number of receive antennas. When these conditions are not fulfilled, IC is better than MRC if the output SINR is low; and MRC yields better performance otherwise. In fact, at the extreme, optimal combining reduces to either MRC or IC: When interference dominates SINR degradation, OC reduces to IC, and when fading dominates the SINR, OC reduces to MRC to optimally mitigate fading.

A complete performance analysis of MRC and OC in MIMO systems with fading and interference assuming multiple receive antennas and a single transmit antenna was undertaken in [8]. While the same techniques can be used to analyze performance under multiple transmit antennas, the mathematics become more involved. The main idea behind the analysis is to investigate the optimal weights for the received signal at all antennas to maximize SNR or SINR. The received signal vector across all antennas after weighting is given by

$$\boldsymbol{r} = H_D w_t b_s + \sum_{i=1}^{L} \sqrt{\Omega_i} h_i b_i + \boldsymbol{n} \tag{1}$$

where H_D is the vector of receive antenna channel gains for the desired signal, w_t is the vector of weights at the transmitter, b_s is the transmitted symbol of interest, b_i is the symbol of the *i*th interfering signal, h_i is the gain of the *i*th interfering signal, and Ω_i is the power of the *i*th interference signal relative to the desired signal. The combiner output is then

$$y = w_{\boldsymbol{r}}^{\boldsymbol{H}} \boldsymbol{r} \tag{2}$$

where w_r are the antenna weights at the transmitter. In MRC, the weights w_r yield the maximum SNR of *y*, and in OC the weights maximize the SINR of *y*. For MRC the weights are well-known to be $w_t = \sqrt{\Omega_D}\boldsymbol{u}$ and $w_r = H_D \boldsymbol{u}$.

It can be shown [9] that the SINR of y assuming weights associated with MRC is given by

$$\gamma = \frac{\Omega_D \lambda}{\sum_{i=1}^{L} \Omega_i \chi_i + \sigma^2} \tag{3}$$

where λ is the maximum eigenvalue of the matrix $H_D^H H_D$ and the χ_i are exponential random variables with unit mean. The SINR distribution thus depends on the distribution of λ and the power of the interferers.

In [8], a closed-form expression for the outage probability of γ is obtained based on the moment-generating function (MGF) of the sum of the interferers $\chi = \sum_i \Omega_i \chi_i$. Differentiating this outage probability yields the distribution of γ. This distribution is then used to obtain the probability of bit error via an MGF analysis assuming any fading distribution on both the desired signal and the interferers. For OC the received signal is given by

$$y_r = \boldsymbol{w}^H \boldsymbol{c}_s b_s + \sqrt{P_I} \sum_{i=1}^{L} w^H c_i b_i \tag{4}$$

where c_s is the fading on the symbol b_s of interest, c_i is the fading on the symbol b_i of the *i*th interferer, and P_I is the weighted power of the interferers. From [8] the optimal weights for OC are given by the vector

$$\boldsymbol{w} = g R^{-1} \boldsymbol{c}_s \tag{5}$$

where *g* is an arbitrary constant and $R = \sum_i c_i c_i^H$ is a Wishart distributed matrix, resulting in SINR $\gamma = P_i^{-1} \boldsymbol{c}_s^H R^{-1} \boldsymbol{c}_s$. The distribution of outage probability associated with this SINR, conditioned on the fading values for the desired and interfering signals, is shown in [9] to be gamma-distributed. The unconditional distribution is obtained in [7] via a MGF analysis, similar to the case of MRC.

The third technique is interference cancellation through beam steering, where array processing under *N* antennas can ideally null out *N-1* interferers. If we assume perfect cancellation of the strongest *N-1* interferers, then performance analysis reduces to finding the outage and bit error probabilities for the residual *L-N-1* interferers that remain after cancellation. These distributions first require the order statistics for the strongest interferers, which are obtained in [10]. The MGF for the received signal and its corresponding pdf is then obtained in closed form, from which outage probability can be obtained. More details can be found in [7].

A performance comparison between OC, MRC, and IC is shown in Figure 4. These numerical results are based on an interference-dominated environment where noise is negligible, and equal-power Rayleigh-fading interferers. The figure shows the outage probability as a function of SIR at each antenna for 2, 3, and 4 receive antennas. Note that as expected, OC has the best performance, since it generalizes both MRC and IC. We also see that IC does worse than MRC except at low SIR, where interference dominates performance degradation and hence canceling interference is the correct strategy. At high SIR values, performance degradation due to multipath fading causes more degradation than interference and hence MRC leads to better performance than IC.

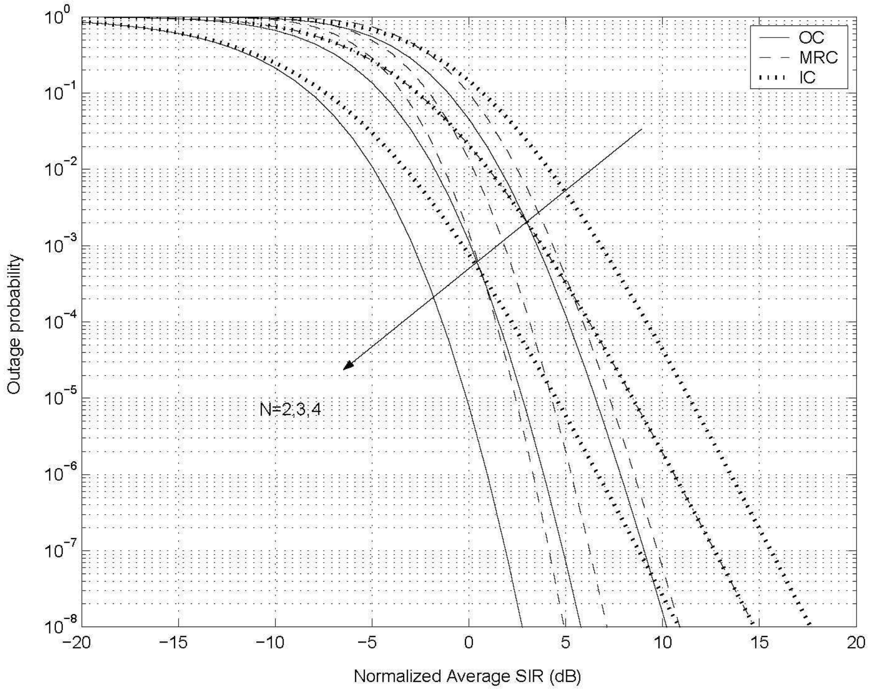

Figure 4 Performance comparison of optimum combining, maximum-ratio combining and interference cancellation

C. MIMO Systems

In this section, we discuss in more detail two fundamental tradeoffs mentioned in the previous section: The first one is between the diversity gain and the multiplexing gain [11]-[12], and the second one between performance and complexity. Focusing for simplicity on 2x2 MIMO systems, two limiting transmission schemes are as follows. One could transmit the same symbol, say s, from the two transmit antennas. In this case, the signal traverses four propagation paths, and, if these are affected by independent fading, the diversity achieved is 4. On the other hand, since only one signal is transmitted per channel use, one has *no multiplexing gain* with respect to single-antenna transmission. If two independent signals are transmitted simultaneously, then each one of them traverses two independent paths, thus achieving diversity 2, but every channel use transmits *two* signals, thus achieving a two-fold multiplexing gain. One may also look for an intermediate situation, where multiplexing gain and diversity gain are traded off: A conceptually simple way of achieving this consists of introducing a certain amount of correlation between the symbols transmitted over the MIMO channel, which is achieved by coding across space and time (*space—time codes*). These codes can be generated by suitably combining good codes designed for single-antenna schemes (e.g., turbo or LDPC codes), or by using *ad hoc designs* (e.g., the Golden Code [13]).

The second tradeoff –that between performance and complexity– is crucial for the receiver design. As optimum receivers are in general very complex to implement, there is a considerable amount of research activity devoted to the design of suboptimum receivers. To motivate this point, consider a MIMO system with an equal number N of receive and transmit antennas, where we denote by s_1, …, s_N the transmitted symbols, and by h_{ij} the fading gain along the propagation path joining transmit antenna j to receive antenna i. These fading gains are organized in a square matrix **H**, and the transmitted symbols in a vector **s**. The received vector **r** can be expressed as

$$\mathbf{r} = \mathbf{H}\mathbf{s} + noise \tag{6}$$

and the receiver's goal consists of detecting the N transmitted signals. The simple device of solving the above system of equations, whereby **s** is the unknown vector, albeit simple, may not be (and in general is not) the best solution, as the presence of noise degrades performance whenever **H** is an ill-conditioned matrix, i.e., a matrix whose largest to the smallest eigenvalue ratio is large. Optimum (maximum-likelihood) detection of the transmitted signals should operate by minimizing, with respect to $s_1, \dots, s_N$, the metric

$$\sum_{i=1}^{N} | r_i - \sum_{j=1}^{N} h_{ij} s_j |^2 \tag{7}$$

However, brute-force minimization of the above requires an exhaustive search among the M^N possible transmitted signal vectors, where M is the signal constellation size, i.e., the number of values taken on by each component of vector **s**. For a 64QAM constellation and N=2, the number of signal pairs to be enumerated amounts to 64^2=4096, which may easily exceed the processing capability of the receiver. Among the possible ways out of this impasse, *sphere detection* plays a central role: This consists of enumerating only a subset of possible signal pairs, after making sure that the optimum pair is not excluded from consideration [11], [12].

A further cause of complexity in MIMO receivers comes from the observation that minimizing the above metric involves the knowledge of the N^2 fading gains (the elements of **H**) appearing in it. This knowledge requires operations of channel estimation.

The WiMAX standard includes some profiles in order to exploit the benefits of MIMO in broadband wireless access systems. These profiles and the main challenges related to their implementation are described in the next section.

1.3 Multiple Antennas in WiMAX Systems

A. Transmit Diversity

One of the WiMAX system profiles is the simple STC scheme proposed by Alamouti [4] for transmit diversity on the downlink. In the IEEE 802.16e-2005 specifications, this scheme is referred to as Matrix A. Originally, Alamouti's transmit diversity was proposed to avoid the use of receive diversity and keep the subscriber stations simple. This technique is applied subcarrier by subcarrier and can be described as follows:

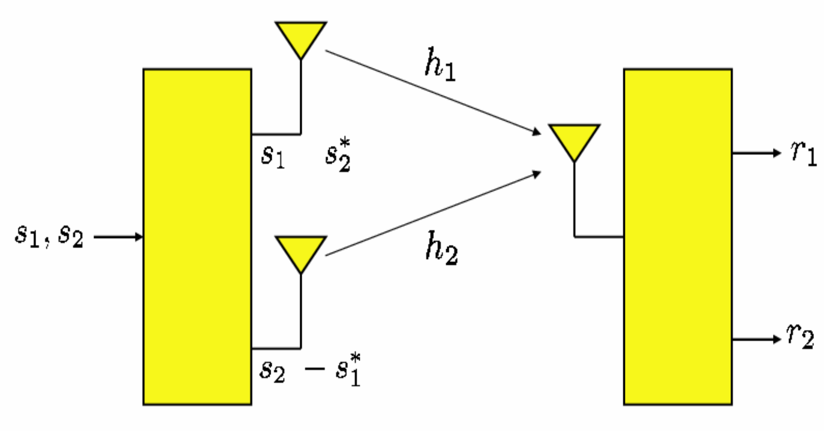

Figure 5 Schematic block diagram of Alamouti's transmit diversity

Suppose that (s_1, s_2) represent a group of two consecutive symbols in the input data stream to be transmitted. During a first symbol period t_1, transmit (Tx) antenna 1 transmits symbol s_1 and Tx antenna 2 transmits symbol s_2. Next, during the second symbol period t_2, Tx antenna 1 transmits symbol s_2^* and Tx antenna 2 transmits symbol $-s_1^*$. Denoting the channel response (at the subcarrier frequency at hand) from Tx1 to the receiver (Rx) by h_1 and the channel response from Tx2 to the receiver by h_2, the received signal samples corresponding to the symbol periods t_1 and t_2 can be written as:

$$r_1 = h_1 s_1 + h_2 s_2 + n_1 \tag{8}$$

$$r_2 = h_1 s_2^* - h_2 s_1^* + n_2 \tag{9}$$

where n_1 and n_2 are additive noise terms.

The receiver computes the following signals to estimate the symbols s_1 and s_2:

$$x_1 = h_1^* r_1 - h_2 r_2^* = \left(|h_1|^2 + |h_2|^2\right) s_1 + h_1^* n_1 - h_2 n_2^* \tag{10}$$

$$x_2 = h_2^* r_1 + h_1 r_2^* = \left(|h_1|^2 + |h_2|^2\right) s_2 + h_2^* n_1 + h_1 n_2^* \tag{11}$$

These expressions clearly show that x_1 (resp. x_2) can be sent to a threshold detector to estimate symbol s_1 (resp. symbol s_2) without interference from the other symbol. Moreover, since the useful signal coefficient is the sum of the squared moduli of two independent fading channels, these estimations benefit from perfect second-order diversity, equivalent to that of Rx diversity under maximum-ratio combining (MRC).

Alamouti's transmit diversity can also be combined with MRC when 2 antennas are used at the receiver. In this scheme, the received signal samples corresponding to the symbol periods t_1 and t_2 can be written as:

$$r_{11} = h_{11} s_1 + h_{12} s_2 + n_{11} \tag{12}$$

$$r_{12} = h_{11} s_2^* - h_{12} s_1^* + n_{12} \tag{13}$$

for the first receive antenna, and

$$r_{21} = h_{21} s_1 + h_{22} s_2 + n_{21} \tag{14}$$

$$r_{22} = h_{21} s_2^* - h_{22} s_1^* + n_{22} \tag{15}$$

for the second receive antenna. In these expressions, h_{ji} designates the channel response from Tx i to Rx j, with $i, j = 1, 2$, and n_{ji} designates the noise on the corresponding channel. This MIMO scheme does not give any spatial multiplexing gain, but it has 4th-order diversity, which can be fully recovered by a simple receiver.

Indeed, the optimum receiver estimates the transmitted symbols s_1 and s_2 using:

$$\begin{aligned} x_1 &= h_{11}^* r_{11} - h_{12} r_{12}^* + h_{21}^* r_{21} - h_{22} r_{22}^* \\ &= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_1 + h_{11}^* n_{11} - h_{12} n_{12}^* + h_{21}^* n_{21} - h_{22} n_{22}^* \end{aligned} \tag{16}$$

$$\begin{aligned} x_2 &= h_{12}^* r_{11} + h_{11} r_{12}^* + h_{22}^* r_{21} + h_{21} r_{22}^* \\ &= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_1 + h_{12}^* n_{11} + h_{11} n_{12}^* + h_{22}^* n_{21} + h_{21} n_{22}^* \end{aligned} \tag{17}$$

and these equations clearly show that the receiver fully recovers the fourth-order diversity of the 2x2 system. It is worth noting that the MRC in this scheme can be modified to take into account the presence of some interferers and thus trade off diversity for interference cancellation.

B. Spatial Multiplexing

The second multiple antenna profile included in WiMAX systems is the 2x2 MIMO technique based on the so-called matrix **B** = $(s_1,\ s_2)^T$. This system performs spatial multiplexing and does not offer any diversity gain from the Tx side. But it does offer a diversity gain of 2 on the receiver side when detected using maximum-likelihood (ML) detection.

To describe the 2x2 spatial multiplexing, we omit the time and frequency dimensions, leaving only the space dimension. The symbols transmitted by Tx1 and Tx2 in parallel are denoted as s_1 and s_2, respectively. Denoting by h_{ji} the channel response from Tx *i* to Rx *j* (*i*, *j* = 1, 2), the signals received by the two Rx antennas are given by

$$r_1 = h_{11} s_1 + h_{12} s_2 + n_1 \tag{18}$$

$$r_2 = h_{21} s_1 + h_{22} s_2 + n_2 \tag{19}$$

which can be written in a matrix form as

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \tag{20}$$

The ML detector makes an exhaustive search over all possible values of the transmitted symbols and decides in favor of (s_1, s_2) which minimizes the Euclidean distance:

$$D(s_1, s_2) = \left\{ \left| r_1 - h_{11}s_1 - h_{12}s_2 \right|^2 + \left| r_2 - h_{21}s_1 - h_{22}s_2 \right|^2 \right\} \tag{21}$$

The complexity of the ML detector grows exponentially with the size of the signal constellation, and this motivates the use of simpler suboptimum detectors in practical applications. Among those are [5], [14], [15]:

1. Zero-forcing (ZF) detectors, which invert the channel matrix. The ZF receiver has a very small complexity that does not depend on the modulation. However, it does not exploit completely the system diversity and suffers from bad performance at low SNR.
2. Minimum mean-square error (MMSE) detectors, which reduce the combined effect of interference between the two parallel channels and additive noise. The MMSE receiver slightly improves the performance of the ZF receiver, but it requires knowledge of the SNR, which can be impractical. Besides, it does not exploit completely the channel diversity either.
3. Decision-feedback receivers, which make a decision on one of the symbols and subtract its interference on the other symbol based on that decision. These receivers offer improved performance when compared to ZF and MMSE receivers, but they are prone to error propagation and still lack optimality, which may lead to large performance losses..
4. Sphere detectors, which reduce the number of symbol values used in the ML detector. Note that this type of detectors may preserve optimality while reducing implementation complexity.

C. Comparison of MIMO Options

Since the Alamouti/MRC scheme and the 2x2 spatial multiplexing scheme have a diversity order of 4 and 2, respectively, the former obviously has better BER performance when the same modulation and coding schemes are used in both systems. Consequently, the Alamouti/MRC scheme can use a higher-level modulation if the two schemes are required to give the same BER performance. Of utmost interest is a performance comparison between the two MIMO schemes when they are used at the same spectral efficiency. (Note that the Alamouti/MRC technique with a modulation scheme transmitting *2m* bits per symbol has the same spectral efficiency as the MIMO spatial multiplexing scheme with a modulation transmitting *m* bits per symbol.)

We have made such a performance comparison using both uncoded and coded systems and different types of channels. Fig. 6 shows the results on an uncorrelated Rayleigh fading channel when the Alamouti/MRC scheme uses 16-QAM and the spatial multiplexing scheme uses QPSK (4 bits per symbol period in both cases). It can be observed that the ZF receiver does not exploit the diversity of the spatial multiplexing scheme and that the slope of its BER curve is only half that of the ML receiver. The other major observation is that the slope of the Alamouti/MRC scheme is twice as large as that of the spatial multiplexing ML receiver, which is due to the diversity factor of 4 for the former and of 2 for the latter. These results, originally reported in [16] and [17] are in agreement with those reported in [18].

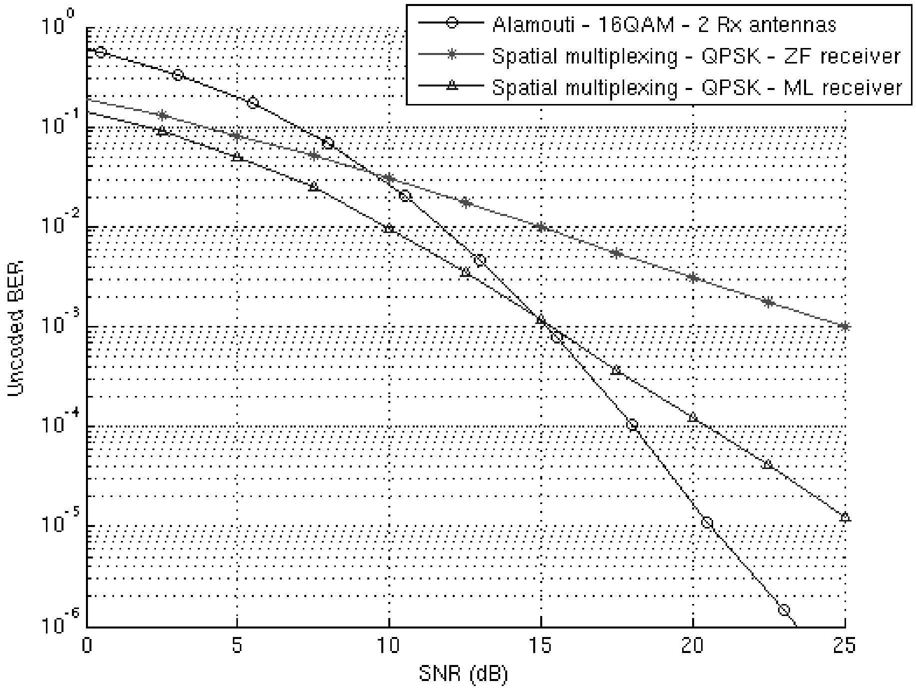

Figure 6 Comparison of Alamouti/MRC with 2x2 spatial multiplexing

As predicted by the respective diversity gains of the two schemes, the results displayed in Fig. 6 confirm that at high SNR values, the simple Alamouti/MRC scheme with 16-QAM achieves better performance than the 2x2 spatial multiplexing MIMO system with ML detection. This suggests that the best MIMO scheme to use in practice depends on the channel SNR and the required throughput as well as on other considerations such as the interference cancellation capability.

To be more specific on the choice between the two MIMO profiles, we summarize in Table I the modulation and coding schemes available in WiMAX systems. (Note that the table is restricted to the convolutional coding schemes included in the standard, and optional interleaving and other coding schemes such as convolutional turbo codes are not considered). The spectral efficiency which appears in this table is for single-antenna systems, and it is of course doubled when spatial multiplexing is used.

Table 1: Constellations and convolutional coding schemes in WiMAX systems

Constellation	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM
Code rate	½	¾	½	¾	½	¾
Spectral efficiency (bits/symbol)	1	1.5	2	3	3	4.5

In single-antenna systems, the throughput is optimized through link adaptation, which selects a constellation and a code rate as a function of the channel. This concept is called adaptive modulation and coding (AMC). The basic idea is to measure the channel quality (for instance by estimating the received power or the received SNR) at the mobile station. If the channel variations are sufficiently slow so that they are essentially constant, the channel quality measurement can be fed back to the base station with estimation error and delay that do not significantly degrade performance. The BS can then adapt the modulation and coding schemes to the channel and optimize the overall spectral efficiency subject to some performance criterion (for instance, the outage probability for a given packet error rate shall be smaller than a predetermined value). Note that dedicated mechanisms such as the Fast Feedback Channel have been incorporated specifically in the standard for the purpose of doing link adaptation.

Fig. 7 illustrates the AMC concept when the performance criterion is that the forward error correction (FEC) block error rate (FBER) must be smaller than 10^{-3}. For different combinations of the modulation and coding options of Table I, the figure shows the SNR thresholds above which the performance criterion is met. (The SNR thresholds are computed for a system using MIMO matrix A at the transmitter, two antennas with MRC at the receiver, and the ITU Pedestrian Channel A corresponding to a speed of 3 km/hour.) For instance, 16QAM with code rate 1/2 cannot be used for SNR values below 7 dB, because it yields an FEC block error rate greater than 10^{-3}. Above this threshold, the modulation meets the performance criterion and leads to a spectral efficiency of 2 bits per symbol. Further, the figure shows that for SNR values exceeding 11dB, 16QAM can also be used with code rate 3/4 and this increases the spectral efficiency from 2 to 3 bits per symbol. Based on the SNR thresholds shown, AMC consists of using the modulation/coding combination that leads to the highest spectral efficiency. The figure shows that some combinations of modulation and coding schemes are not useful on the considered channel for the performance criterion used. For instance, it is meaningless to use 64QAM with code rate 1/2, because 16QAM with code rate 3/4 gives the same spectral efficiency and has a lower SNR threshold.

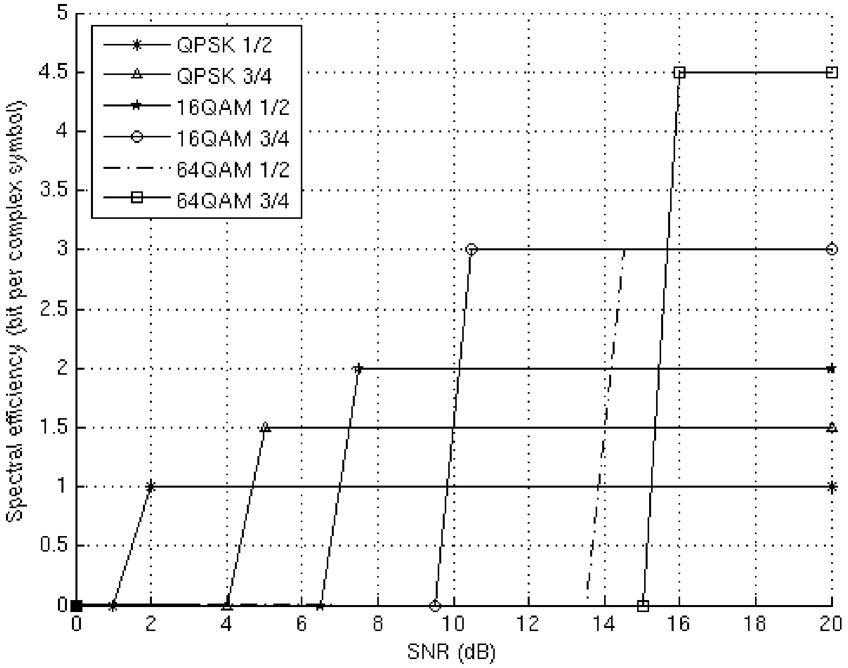

Figure 7 Operating SNR thresholds for adaptive modulation and coding (ITU Pedestrian Channel A, speed = 3 km/h, FBER = 10^{-3}).

Returning now to the MIMO schemes in WiMAX systems, the best way to handle them is to add the MIMO dimension to modulation and coding, and select the best MIMO/Modulation/Coding combination through link adaptation. Fig. 8 depicts the 7 useful combinations for link adaptation over a pedestrian channel. Based on the results of this figure, MIMO matrix B (spatial multiplexing) will be usable with 16QAM and code rate 3/4 at SNR values higher than 22 dB yielding a spectral efficiency of 6 bits per symbol. Furthermore, at SNR values higher than 30 dB, this system can use 64QAM and code rate 3/4 leading to a spectral efficiency of 9 bits per symbol. This represents a significant increase of throughput compared to a MIMO matrix A system whose spectral efficiency is limited to 4.5 bits per symbol. It should be pointed out however that, in practice, the channel correlation due to the small distance between the receive antennas on the mobile station may seriously affect these results, and more particularly the Matrix B performance. Interference can also significantly impact the performance tradeoffs between Matrices A and B.

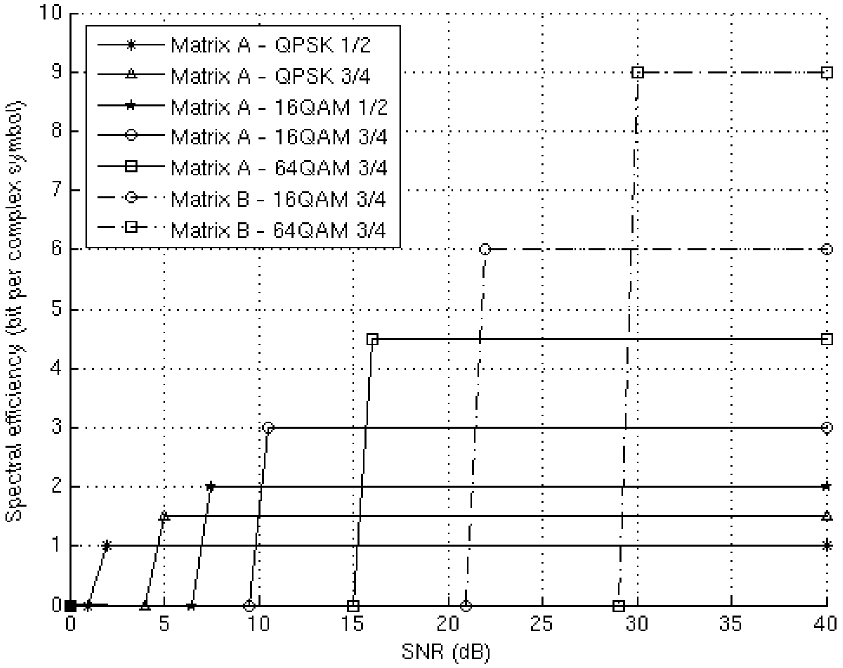

Figure 8 Operating SNR thresholds for adaptive modulation, coding and MIMO combinations (ITU Pedestrian Channel A, speed = 3 km/h, FBER = 10^{-3}).

1.4 Summary and Conclusions

The Mobile WiMAX standard includes many different features and options to make the best use of the wireless channel characteristics. These include adaptive modulation and coding, and multiple antenna (MIMO) techniques such as transmit/receive diversity and spatial multiplexing. In this paper, we first discussed the use of multiple antenna techniques in a general context and the tradeoffs between diversity, multiplexing gain and interference cancellation. Next, we described the two MIMO schemes included in the mobile WiMAX system specifications and analyzed their performance using the ITU pedestrian B channel model with a pedestrian speed of 3 km/h and assuming perfect channel state information and uncorrelated channels. It was first observed that at high SNR values, Alamouti's STC with MRC at the receiver significantly outperforms Spatial Multiplexing when the two systems employ modulation schemes leading to the same spectral efficiency. Next, for different modulation, coding and MIMO schemes, the SNR values leading to a BER of 10^{-3} were computed and the achievable spectral efficiency vs. SNR was plotted indication which scheme can be used in which SNR region. The results indicated that MIMO Matrix A must be used except at very high SNR values, where Matrix B can lead to an increased spectral efficiency.

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